ELECTRICAL MODELING OF MERCURY FOR OPTIMAL MACHINE DESIGN AND PERFORMANCE ESTIMATION*

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Abstract

Mercury is a new pulsed-power generator at NRL, having been transferred from FZK (Forschungszentrum Karlsruhe, Germany) where it was known as KALIF-HELIA[1,2]. Mercury is an MIVA (magnetically-insulated inductive voltage adder) designed to produce 50-ns pulses with load voltages up to 6 MV at a current of 360 kA and deliver 100-kJ of energy to the load[3]. The inductive and resistive components connecting the Marx bank and the intermediate stores have been reconfigured to fit into one "machine tank" and to improve energy transfer, allowing for a reduced Marx charge voltage. A detailed circuit model was developed for Mercury based on an earlier model for KALIF-HELIA and updated to include new information and data from FZK. Circuit element values for the MIVA and the load were determined through PIC simulations. Good agreement between measured and calculated current and voltage peaks was found using the model fed by voltage signals measured upstream of the MIVA on KALIF-HELIA. Detailed modeling has shown that the original design parameters of the machine can be met at NRL.

I. DESIGN OF THE MERCURY MACHINE TANK

KALIF-HELIA had separate oil tanks for the Marx and the IS (intermediate-store) bottles. For Mercury, these tanks were consolidated into one "machine" tank due to space constraints. A few other changes are being made to improve energy transfer from the Marx to the IS bottles. This should allow Mercury to operate at a lower Marx charge voltage, thereby increasing the lifetime of the capacitors. The Marx is a "Sandia-style" design with 36, 2.2-μF capacitors, which are rated for 100 kV and were operated at 95 kV at FZK. The four IS bottles are 4' long with a 4' OD with a capacitance of 9 nF each. A series output resistor between Marx and IS limits Marx current. When the IS bottles are charged, a laser-triggered switch closes, connecting each IS bottle to three pulse-forming lines. A diagram of the new machine tank is shown in Fig. 1.

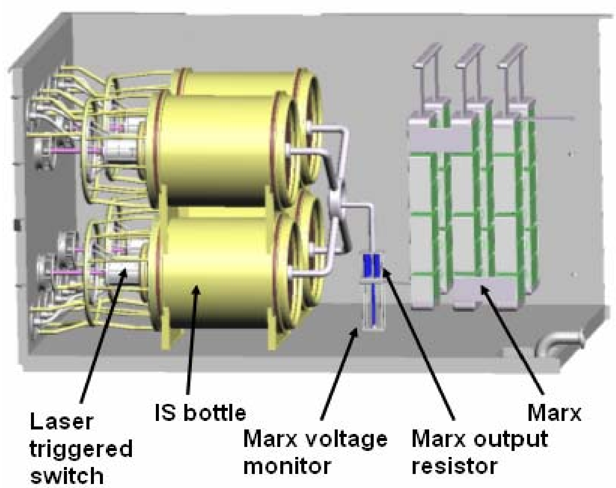

Figure 1. Diagram of the Mercury machine tank.

To understand how changes to the machine tank would affect performance, an existing circuit model for KALIF-HELIA (supplied by Titan PSD) was improved with data from FZK. This model was then used as the basis for a model of Mercury. Simplified diagrams of the Marx-IS portion of these circuit models are shown in Fig. 2. The inductance between Marx and IS is lowered by a factor of two for Mercury due to the compactness of the new machine tank, but this has little effect on the circuit due to the large inductance of the Marx.

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14. ABSTRACT

Mercury is a new pulsed-power generator at NRL, having been transferred from FZK (Forschungszentrum Karlsruhe, Germany) where it was known as KALIFHELIA[1,2]. Mercury is an MIVA (magneticallyinsulated inductive voltage adder) designed to produce 50-ns pulses with load voltages up to 6 MV at a current of 360 kA and deliver 100-kJ of energy to the load[3]. The inductive and resistive components connecting the Marx bank and the intermediate stores have been reconfigured to fit into one machine tank and to improve energy transfer, allowing for a reduced Marx charge voltage. A detailed circuit model was developed for Mercury based on an earlier model for KALIF-HELIA and updated to include new information and data from FZK. Circuit element values for the MIVA and the load were determined through PIC simulations. Good agreement between measured and calculated current and voltage peaks was found using the model fed by voltage signals measured upstream of the MIVA on KALIF-HELIA. Detailed modeling has shown that the original design parameters of the machine can be met at NRL.

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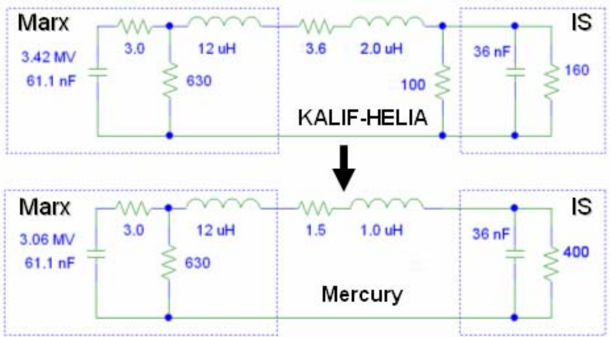

Figure 2. Simplified circuit diagrams showing changes made in the Marx-IS system for Mercury.

The main changes to the circuit being made for Mercury are the elimination of the IS shunt resistor and a lower value for the Marx output resistor. The IS shunt resistor was installed by FZK to act as a safety mechanism in the event that the laser switches failed. However, it is now felt that the RC time of the 36-nF IS and 100-Ω shunt resistor would be too great to prevent damage. The Marx output resistor had a rather large value of 3.6 Ω at FZK in order to keep the Marx switch currents well under their 150-kA rating. However, with the IS shunt resistor removed the output resistor can be reduced to 1.5 Ω (the lowest value obtainable with the existing hardware) and the Marx current required to achieve a certain IS voltage is actually reduced. The hardware from the IS shunt resistor has been reused as a high-impedance Marx voltage monitor (see Fig. 1).

The resistance of the water inside the IS bottles also acts as a shunt resistance. KALIF-HELIA operated with a water resistivity of ~0.8 MΩ-cm, giving an effective shunt resistance of 160 Ω. We plan to increase the resistivity to at least 2 MΩ-cm for a resistance of >400 Ω.

All of these changes will allow us to increase the IS voltage while decreasing the Marx charge voltage from 95 kV to 85 kV. A comparison between the Marx currents and IS bottle voltages for KALIF-HELIA and Mercury is shown in Figs. 3 and 4, respectively.

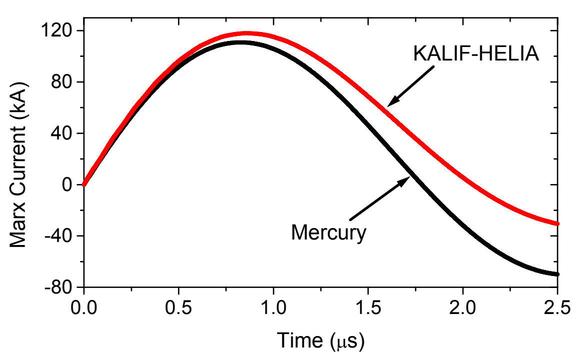

Figure 3. Plots of Marx current measured on KALIF-HELIA and simulated for Mercury.

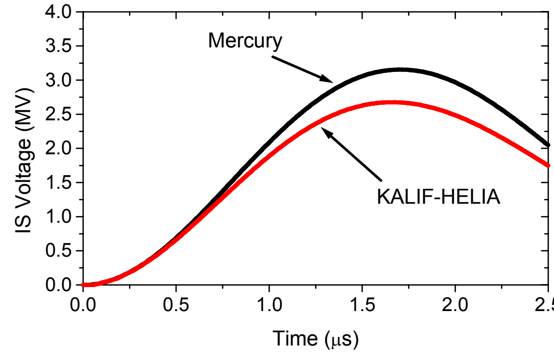

Figure 4. Plots of IS voltage measured on KALIF-HELIA and simulated for Mercury.

II. MERCURY PERFORMANCE ESTIMATION

The circuit model for Mercury was further refined through PIC code simulations of the MIVA and by benchmarking against KALIF-HELIA shot data. The OLS (output-line-second, see Fig. 5) section of the 12 water pulse-forming-lines was helpful in both of these tasks. The 2-way transit time of the OLS section, 85 ns, is greater than the main pulse width of 50 ns. So, from a modeling point of view, the OLS section can act as either a fixed impedance source or load, allowing us to split the modeling problem at the OLS section.

All 12 OLS voltage-monitor signals, V_{OLS}, were recorded on many of last KALIF-HELIA shots. These data were used to analyze the performance of the machine up to the OLS section and to separately analyze the performance of the MIVA. A diagram of Mercury from the IS bottles to the MIVA is shown in Fig. 5, indicating the location of the OLS voltage monitor, V_{OLS}.

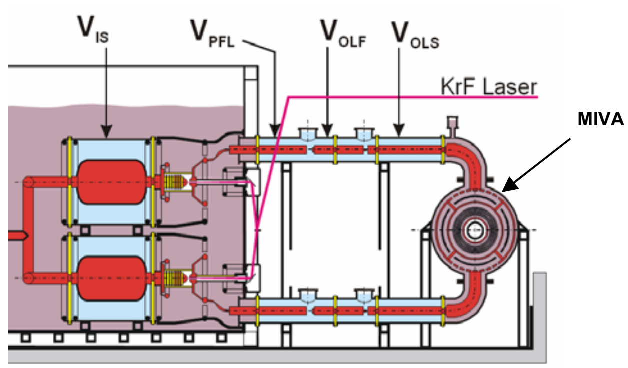

Figure 5. Diagram of Mercury from IS bottles to MIVA.

A. Water-Switch Resistance

Comparisons of measured V_{PFL} and V_{OLS} signals to those from circuit simulations indicate about a factor of ten larger water switch resistance than anticipated in the design of KALIF-HELIA. There are two water switches in the pulse lines, an output switch between PFL (pulse-forming-line) and OLF (output-line-first) sections and a prepulse switch between OLF and OLS sections. In the last several shots on KALIF-HELIA, the output switch gap was 40 mm and the prepulse switch gap was 10 mm. The on-state switch resistance required in the model to get agreement with measurements is about 0.3 Ω/cm, or 1.2 Ω total for each output switch, which is much higher than that the design value, 0.133 Ω. The corresponding electric field in the switch region is 55 kV/cm, which is close to the 30 to 50 kV/cm recently measured by Titan PSD on other machines. Switch resistance results in a total energy loss of about 20 kJ.

B. MAGIC Simulation of MIVA

In order to better estimate the performance of Mercury, the circuit model for the MIVA had to be improved. The MIVA is modeled as six, 2.3-ns long transmission line sections, one after every radial feed (spaced 0.65 m apart), and then one, 1.3-ns long section representing the MITL (magnetically-insulated transmission line) to the load. When electrons are present in the MIVA, the effective impedance is reduced. Better circuit model fidelity was achieved by modeling the MIVA in 2D with the PIC code MAGIC [4]. The six input ports of the simulation were fed with idealized versions of measured OLS signals (1-MV peak, 50-ns FWHM pulses with 25-ns smooth rise and fall and 6-ns timing shift between the first three cells and the last three cells). The load was the large-area e-beam diode used on KALIF-HELIA. The results of these simulations were used to calculate Z_{flow} impedances for MIVA sections of the transmission-model and the load impedance as functions of the diode AK gap. As shown in Fig. 6, there is almost no change in impedances with AK gap, except for the load.

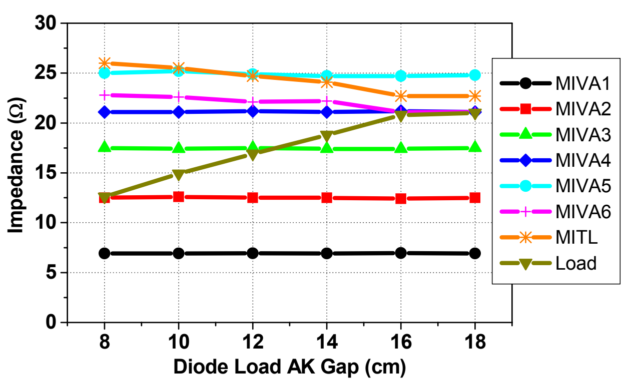

Figure 6. MIVA, MITL and Load impedances as functions of the diode load AK gap from PIC simulation.

The peak load voltages and energies delivered to the load were also extracted from the PIC simulation as shown in Fig. 7. The energy and voltage continue to rise with AK gap until starting to plateau when the load impedance rises to ~20 Ω. This verifies that the matched load for Mercury is determined by the effective 20.4-Ω impedance of the OLS feeds (two 6.8-Ω feeds in parallel for each of six series cells).

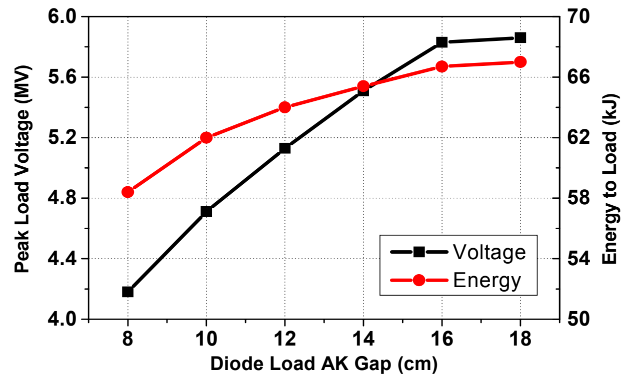

Figure 7. Peak load voltage and energy to the load as functions of diode load AK gap from PIC simulation.

In order to gauge the validity of modeling the MIVA as fixed-impedance transmission-line elements, a Bertha [5] model of the MAGIC simulation was made where fixed Z_{flow} values, shown in Fig. 6, were assigned to the elements. A comparison of the load currents between the Bertha and MAGIC models, given the same 1.0-MV inputs described earlier, is shown in Fig. 8. A 16.2-Ω load was used for this comparison as this corresponds to the 11.3-cm diode AK-gap (see Fig. 6) used on most of the later KALIF-HELIA shots. The agreement is quite good, except for the first 10 ns of the pulse when MITL flow is being established.

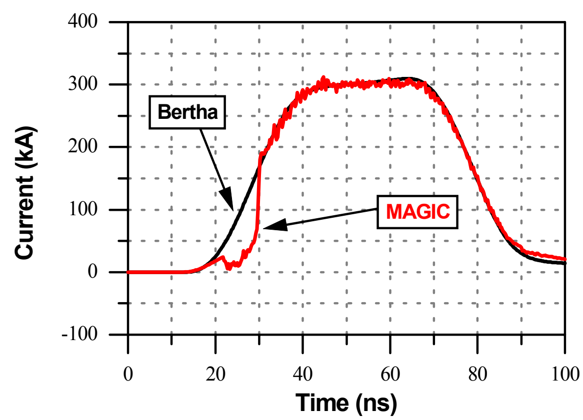

Figure 8. Comparison of load currents calculated by Bertha (black) and MAGIC (red) given 1.0-MV inputs.

C. Bertha Analysis of KALIF-HELIA Data

Starting with the 12 measured V_{OLS} signals from several KALIF-HELIA shots, the Bertha model of the MIVA was used to compare measured and simulated load currents. The agreement shown in Fig. 9 for shot O146 was typical for the shots that were checked.

The delayed rise of the measured load current, when compared to the Bertha model, is similar to that when comparing MAGIC simulations to the Bertha model (see Fig. 8). A new magnetically-insulated transmission-line model is being developed to improve the fidelity of these simulations by providing a time-dependent impedance.[6]

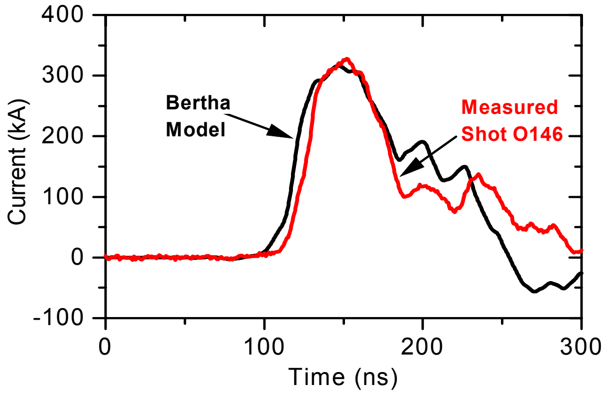

Figure 9. Comparison of measured and calculated (by injecting measured V_{OLS} signals into model) load currents.

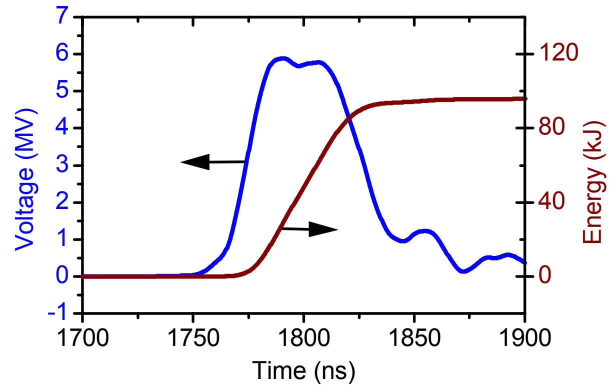

Figure 10. Load voltage and energy expected from Mercury into a 16.2-Ω load.

The load voltage was determined for KALIF-HELIA by summing the six cell voltages after shifting 2-ns per cell to account for transit time. The peak of this voltage was also found to be in good agreement with the Bertha model described above. On shot O146, e.g., the measured peak load voltage was 4.98 MV and that calculated from the V_{OLS} signals was 5.08 MV.

Achieving the 6-MV and 100-kJ design goal requires larger OLS voltages than those measured on KALIF-HELIA (~1.0-MV peak). The MAGIC model required 1.3-MV peak inputs to reach this goal with a 16.2-Ω load. PIC simulations indicate that MIVA impedances are largely unaffected by this increase in input level unless electron emission occurs in the radial feeds. Mercury will have new feed-gap expanders installed to increase the feed gap from 4.5 to 7.0 cm. This should prevent electron emission in the radial feeds.

D. Bertha Estimate of Mercury Performance

The full circuit model for Mercury was used to estimate the performance with the same 16.2-Ω load used on KALIF-HELIA and the optimizations described earlier. The calculated V_{OLS} signals have a peak of 1.2 MV and a 53-ns FWHM. The expected load voltage and energy are shown in Fig. 10. The load voltage peaks at 5.9 MV and the load energy, just after the main pulse, is 96 kJ. The effects of switch jitter are not included in this calculation, although ~5 kJ loss due to jitter is expected. This loss estimate is based on an average standard deviation, σ=1.5 ns, of the timing error in V_{OLS} signals from KALIF-HELIA data with 40-mm output switch gaps and 95-kV Marx charge voltage (not including the last few shots, where a fault in PFL #3 may have affected the jitter).

There are a few ways to further increase the output of Mercury, if required. The load energy can be increased by about 6 kJ using a matched load. The Marx charge voltage can also be raised, although this would increase the risk of damage to the machine. Also, MAGIC simulations have shown that a narrower center conductor can be used to maximize load voltage. Other PIC simulations were performed to design a rod-pinch diode for Mercury.[7]

III. SUMMARY

A new machine tank was designed for Mercury to house both the Marx and the IS bottles. Bertha modeling indicates that changes being made to the Marx-IS circuit will allow increased IS voltage with lower Marx charge voltage and peak current for Mercury compared to KALIF-HELIA.

Performance estimation of Mercury was aided by the long electrical length of the OLS section of the pulse-forming lines and KALIF-HELIA data from the V_{OLS} monitors. MAGIC simulations were used to assign Z_{flow} impedance values to the MIVA and load elements of the circuit models. The performance of the MIVA at FZK was gauged by comparing calculated and measured load currents. The new circuit model was used to show that the original design parameters of 6 MV at a current of 360 kA, delivering 100-kJ to a load, can be met.

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